TWO-PHASE FLOW TURBINE FOR COGENERATION, GEOTHERMAL, SOLAR AND OTHER APPLICATIONS

FEASIBILITY ANALYSIS AND FINAL EISG REPORT

Prepared For:
California Energy Commission
Energy Innovations Small Grant Program

Prepared By:
FAS Engineering

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ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

FEASIBILITY ANALYSIS REPORT (FAR)

TWO-PHASE FLOW TURBINE FOR COGENERATION, GEOTHERMAL, SOLAR AND OTHER APPLICATIONS

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Grant #: 99-33
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Term: Aug 2000 – May 2002
PIER Subject Area: Renewable Energy Technologies

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LEGAL NOTICE

PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which $3 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)
    - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/research/index.html.

Two-Phase Flow Turbine For Cogeneration, Geothermal, Solar And Other Applications

EISG Grant # 99-33

Awardee:	FAS Engineering, Inc.
Principal Investigator:	Dr. Gracio Fabris
PI Contact Info:	Phone: (818) 952-0217; Email: gfabris@earthlink.net

Grant Funding:	$75,000
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Introduction

There are many sources of boiling hot water currently not fully utilized for electricity production. These sources include geothermal, solar thermal, and bottoming cycles of large steam power plants. The energy in the heated water can be transferred to a thermodynamic working fluid to generate electrical power. Because of the water is only under moderately high temperature and pressure, the working fluids often operate in the two-phase region (water and steam together, for example). Energy conversion devices that work in the two-phase region are typically low in efficiency and often suffer from poor durability. A possibility exists to greatly improve the overall cycle thermal efficiency. Impulse type two-phase turbines have moderate turbine efficiencies but a very high turbine blade erosion rate due to impingement by high velocity, intermittent, individual liquid droplets. While reaction turbines are more reliable than impulse turbines, the efficiencies of existing two-phase reaction turbines are poor. If the efficiency of two-phase reaction turbines can be increased to reasonable levels, then most of the advantages of two-phase cycles could be realized practically in many low energy conversion cycles.

The researcher's goal in this project was to show that a newly designed and patented turbine could operate at a turbine efficiency of at least 50%. For clarity, understand that because the best existing two-phase reaction turbine operates at 33%, the new turbine's efficiency will be a 50% relative improvement as well as an absolute efficiency of 50%. The researcher designed and tested improvements to the expansion nozzle of a two-phase turbine. To improve the turbine efficiency, the researcher proposed a proprietary nozzle design with a long spiral flow-path.

The researcher analyzed the prior-art of two-phase reaction turbines and identified two major efficiency loss mechanisms. The first mechanism is the slip-loss induced by very large lateral separation forces. These very large forces separate liquid to one side of the nozzles and vapor to the other side. The force acting on the vapor and liquid at a given operating condition within the reaction turbine is constant. However, the mass of liquid per volume unit exceeds the mass of vapor. Therefore the accelerations of the liquid and the vapor are different and separation occurs. The second loss mechanism is the abruptness in flashing of liquid to vapor. In two-phase reaction turbines this effect is due to high over-pressurization (at pressures about 10 times higher than saturation pressure) and very short, inefficient nozzles. If these mechanisms could be eliminated, turbine efficiency would improve greatly.

Objectives

The goal of this project was to determine the feasibility of a two-phase flow turbine incorporating a curved reaction nozzle to provide at least 50% conversion efficiency.

The researcher established the following project objectives:

1. Build a 25 kW prototype two-phase reaction turbine that operates at 20,000 RPM..
2. Build a turbine test facility capable of heating water to 435°F and 350 PSIG, representative of the target applications, and configured for testing the two-phase turbine.
3. Test the prototype two-phase turbine, demonstrating efficiency of at least 50%.

Outcomes

1. The researcher completed design drawings and fabricated a 17-inch diameter turbine. The material yield stress point allowed operation up to approximately 50,000 RPM. The prototype turbine was operated several times at rotational speeds of 20,000 RPM, about 2.6 times higher RPM than prior two-phase reaction turbines.
2. The researcher constructed and instrumented a blow-down style test facility. This facility heated and stored 200 gallons of water at the required temperature and pressure (435°F and 350 PSIG). Pressure, temperature, and flow meters were installed on the two-inch blow-down pipe feeding the turbine. Flow was controlled by a two-inch ball valve. Additional equipment included a three-phase generator chain driven by the turbine and coupled to three balanced and cooled load resistors. Typical laboratory instrumentation was installed.
3. The researcher conducted multiple test runs of the two-phase turbine. The results for eight runs, tabulated in Appendix A, indicate turbine efficiencies of 50.1% at turbine design speed.
4. An unexpected result was the challenge of maintaining the ball bearings in the turbine. The inner bearing race was mated to the hot input shaft while the outer race was attached to a much cooler structure. During the test runs the inner race heated and expanded, using up the tolerance of the stainless steel ball bearing. To avoid bearing seizure during test runs, the researcher used chromium steel bearings with wider tolerances. Some of the bearings still seized and the others rusted quickly, but satisfactory test runs were accomplished in the time available.

Conclusions

1. The two-phase reaction turbine was successfully built to design. The complex curved flow path for the two-phase fluid required a numerical controlled machine tool driven by the design computer code to accurately implement the design. This is not a problem in a modern machine shop.
2. The blow-down test facility built as part of this project was adequate to obtain early development phase results. That facility allowed the researcher to obtain data sets for operational intervals of minutes. However, electric generator products are expected to run and generate power for intervals of 20,000 to 30,000 hours between overhauls. Long-term considerations, such as erosion of the turbine nozzle, were not addressed in this project.
3. The researcher reported (Appendix A) the prior art in reaction turbines was generated at Lawrence Livermore National Laboratory (LLNL). LLNL tested a reaction turbine that demonstrated efficiency of only 33%. The two-phase turbine tested in this project demonstrates higher efficiency than the LLNL turbine in almost all test cases. The approximately 50% turbine efficiency demonstrated in this project is a major improvement over the 33% efficiency of the prior art (See conclusion in #5 below). Larger reaction turbines may exhibit increased efficiency due to scale effects.

4. Bearing failure plagued this project. For future test rigs the researcher should retain a bearing expert with experience in high-speed turbo-machinery. Such an expert might recommend other bearing designs that do not rely on rolling elements.
5. The PA suggests caution in accepting the reported turbine efficiency. The approach used to measure the power generated and hence the efficiency of the two-phase reaction turbine under test may have yielded overly optimistic results. The turbine drove an electric generator and the electrical power was measured. The generator was chain driven. A transfer efficiency coefficient of 0.85 was assumed for the chain transfer, and a generator efficiency coefficient of 0.85 was assumed. While these may be reasonable engineering approximations, it is unfortunate the researcher did not measure these coefficients. To understand the critical nature of these assumptions, consider the limiting case of perfect power transfer and generation. If the efficiency coefficients were both 1.0, the 50% efficiency reported would reduce to only 36%. That is still a 10% improvement over prior art. In fact, actual transfer efficiencies and generator efficiency are less than 1.0 resulting in a turbine efficiency of over 36%. Nonetheless, any potential industrial partner would want to have greater knowledge of the expected turbine efficiency and how it was measured.

Benefits to California

Many sources of boiling hot thermal energy are available in California. These include geothermal, solar thermal facilities, and bottoming cycles of large power plants. Current recovery of these vast resources is hindered by lack of energy conversion devices that can operate efficiently while enduring the mechanical stresses of two-phase flow. If the turbine demonstrated in this project proves to be commercially viable, numerous new sources of energy could become available to produce electricity for California ratepayers.

This project did not perform a life cycle cost analysis. Thus it is not possible to determine the financial impact of this development to ratepayers.

Recommendations

The results of this project support the feasibility statement for this project. A turbine efficiency of approximately 50% has been reported. The PA recommends calibrations of the researcher’s test apparatus to more accurately determine this efficiency. Even in the range of 40 to 50% efficiency, this turbine is a major improvement over prior art. Rather than continue to develop improved turbine designs that operate at higher speeds, temperatures and pressures, the PA recommends the researcher reduce the design with proven feasibility to commercial practice. The PA recommends the researcher find a commercialization partner. With that partner the researcher should develop designs that have high reliability, durability, maintainability, and safety. In addition the researcher should perform a life cycle cost analysis to ascertain profitability of an energy cycle that includes the 50% efficient two-phase turbine.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities are tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: http://www.energy.ca.gov/research/innovations and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market

While the researcher became familiar with potential applications and the markets for this technology, he halted his preliminary marketing attempts when he discovered the need to have a prototype to demonstrate. The researcher has given no indication that he is dealing with a potential commercialization partner who would help him determine the market requirements for his turbine. A marketing requirements specification details the customer-specific, technical needs in each of the targeted markets. Advanced development engineers must know how the product will be used before continuing the development.

Engineering/Technical

Engineering and technical work for the design, building, and test of the proposed turbine was successfully carried out. Turbine efficiencies of ~50% were reported in this project. This was achieved by incorporating a curved reaction nozzle and high turbine-rotor tip speeds. Turbine-rotor tip velocities were 2.6 times higher than in prior two-phase reaction turbines. Because of the large amount of energy stored in a high-speed rotor, turbines with high rotor tip speeds require some of the highest metallurgical specification, analysis, standards, and testing to prevent injury. Any continuing work must focus on safety, reliability, and durability issues.

Legal/Contractual

The researcher holds a patent. He also holds another patent on a single-cycle heat activated heat pump, which used the subject two-phase reaction turbine as its key component. There are no patent issues to be resolved.

Environmental, Safety, Risk Assessments/ Quality Plans

Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental**.** None of these plans have been developed at this time. A quality plan is imperative to continue onto the next phase. The recommended quality plan should include materials specifications, manufacturing methods, failure modes, and metallurgical and mechanical test protocols. Accelerated life cycle testing should be performed to ascertain the failure modes and the expected life of the turbine rotor. The power generation industry is very conservative. The first customer expects to buy components that have been tested for over 20,000 hours. Experience of this type is typically gained by advanced laboratory testing and field-testing of prototypes at sites of customers willing to take a higher degree of risk.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere.

Production Readiness/Commercialization

There have been no disclosures of the project results to potential manufacturers. There is no production readiness plan and no "should cost" estimates.

Public Benefits

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is to increase the affordability of electricity to California ratepayers. Currently under exploited heat sources could be more viable if this turbine were to be produced at a price acceptable to the market. Unfortunately, the researcher has not produced product cost projections that would allow the PA to determine cost savings to the California ratepayer.

Program Administrator Assessment

After taking into consideration: (a) research findings in the grant project, (b) overall development status as determined by stages and gates and, (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow on funding within the PIER program.

The sources of follow-on funding include commercial, partner, venture funding, DOE and other federal sources, and California's PIER program. The conditions for PIER funding include (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation and, (c) successful evaluation of the proposal.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

DOE F 241.3 (2-01) p. 2 of 4 **ANNOUNCEMENT**	**UNITED STATES DEPARTMENT OF ENERGY (DOE)** Scientific and Technical Information (STI) For Financial Assistance Recipients and Non-M&O/M&I Contractors	*OMB Control No. 1910-1400*

PART II: STI PRODUCT MEDIA/FORMAT and **LOCATION/TRANSMISSION**

(To be completed by Recipient/Contractor)

A. Media/Format Information:

1. MEDIUM OF STI PRODUCT IS:

X Electronic Document ☐ Computer medium
☐ Audiovisual material ☐ Paper
☐ No full-text

2. SIZE OF STI PRODUCT 50 pages

3. SPECIFY FILE FORMAT OF ELECTRONIC DOCUMENT BEING TRANSMITTED, INDICATE:

☐ SGML X HTML ☐ XML ☐ PDF Normal ☐ PDF Image

☐ WP-Indicate Version *(5.0 or greater)* 5.0
Platform/operating system ____

☐ MS-Indicate Version *(5.0 or greater)* 5.0
Platform/operating system ____

☐ Postscript ____

4. IF COMPUTER MEDIUM OR AUDIOVISUAL

a. Quantity/type *(specify)* ____

b. Machine compatibility *(specify)* ____

PART III: STI PRODUCT REVIEW/RELEASE INFORMATION

(To be completed by DOE)

A. STI Product Reporting Requirement Review:

☐ 1. THIS DELIVERABLE COMPLETES ALL REQUIRED DELIVERABLES FOR THIS AWARD

2. THIS DELIVERABLE FULFILLS A TECHNICAL REPORTING REQUIREMENT, BUT SHOULD NOT BE DISSEMINATED BEYOND DOE.

B. DOE Releasing Official

☐ 1. I VERIFY THAT ALL NECESSARY REVIEWS HAVE BEEN COMPLETED AS DESCRIBED IN DOE G 241.1-1A, PART II, SECTION 3.0 AND THAT THE STI PRODUCT SHOULD BE RELEASED IN ACCORDANCE WITH THE INTELLECTUAL PROPERTY/DISTRIBUTION LIMITATION

<table>
<tr><td>c. Other information about product format a user needs to know: ________________</td><td>ABOVE.</td></tr>
<tr><td>B. Transmission Information:
STI PRODUCT IS BEING TRANSMITTED:
☐ 1. Electronic via Elink
X 2. Via mail or shipment to address indicated in award document (Paper products, CD-ROM, diskettes, videocassettes, et.)
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☐ 2a. Information product file name (of transmitted electronic format)
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Date __________
(mm/dd/yyyy)
E-mail ________________
Phone ________________</td></tr>
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UNITED STATES DEPARTMENT OF ENERGY

FINAL REPORT

IMPROVED ENERGY CONVERSION FOR GEOTHERMAL POWER PLANTS

Grant #: DE-FC36-99GO10442; Grant Funding: $75,000
Term: October 1, 1999 – May 1, 2002

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ENERGY INNOVATION SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

TWO-PHASE FLOW TURBINE FOR COGENERATION, GEOTHERMAL, SOLAR AND OTHER APPLICATIONS

Grant #: 51536A/99-33; Grant Funding: $75,000.
Term: August 1, 2000 – May 1, 2002
PIER SUBJECT Area: Renewable Energy

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Acknowledgement

Funding by the Geothermal Division of the Energy Efficiency Office of the United States Department of Energy under Innovative Geothermal Energy Technology Program is greatly appreciated. In the same way co-funding by the California Energy Commission under Energy Innovation Small Grant Program is also greatly appreciated.

Even though a project of this degree of complexities and technical difficulties normally requires appreciably higher funding it is certain that without actually provided funding by the DOE and the CEC this project would not have been initiated and would not have been accomplished. There was no substitute to experimental verification of performance of a novel two-phase flow turbine. There was no way that two-phase flow of this level of complexity could be a priory computer simulated and predicted (in advance, based on all prior two-phase flow R&D) with an acceptable level of expected accuracy. We do hope and believe that this project and the technology will provide good return on the funds invested by the DOE and the CEC.

Abstract

The purpose of this project was to build high temperature test facility, built first prototype of patented novel two-phase flow thermal turbine with rotor diameter of 17 inches capable safely operating at high rotational speeds of 20,000 RPM, and delivering mechanical shaft power of up to 25 kW.

The objective of this project was to carry out testing of the first turbine prototype and to verify that this turbine has improved performance over prior two-phase turbines of similar size.

This challenging project has been successfully carried out. The turbine rotor has been repeatedly run at rotational speeds of up to 20,000. The rotor tip speeds were up to 1480 ft/s, which is even more than two and half times higher speed than with almost identical diameter rotor of prior art 100% two-phase flow reaction turbine, though the prior turbine was driven by 40% higher specific enthalpy drop. The turbine efficiency improvements were up to 50% over the turbine efficiencies of the prior art 100% two-phase reaction turbines.

Further significant improvements in the turbine efficiency are possible by recovering most of the exiting kinetic energy of fluid, and by increasing the size of the turbine as it would be anyway required in most applications.

It is very important that two-phase turbines are uniquely suitable for applications in topping, bottoming or standalone trilateral thermal energy conversions cycle, which

would extract mechanical energy from parts of processes where presently the "thermodynamic availability" is completely wasted. In such a way applications of these turbines would definitively result in increase of 20 to 50% in the overall efficiencies of energy conversion systems in numerous applications.

Key words for computer searches: Higher efficiency two-phase turbine, higher efficiency thermal energy conversion cycles, cogeneration, solar energy, renewable energy, geothermal energy, waste heat utilization.

Executive Summary

1. Introduction

It is known that application of an efficient energy conversion device (turbine) in trilateral (topping, bottoming and/or standalone) thermal energy conversion cycles could increase the overall efficiency of many energy conversion systems by 10 to 50%. However the trilateral cycles almost always occur in two-phase region of a thermodynamic working fluid. This means that two-phase turbines are main candidates to be the prime movers in such systems.

Impulse type two-phase turbines have moderate turbine efficiencies but very high erosion rate of turbine blades due to impingement by high velocity intermittent (individual) liquid droplets. Efficiencies of prior technology two-phase reaction turbines were poor. If the turbine efficiency of two-phase reaction turbines can be increased to a reasonable levels, then most of the advantages of trilateral cycles could be practically realized in many energy conversion systems, i.e. the overall efficiencies would be substantially increased.

Through careful analysis we have realized that in prior art two-phase reaction turbines there were two major efficiency loss mechanisms, which could be almost completely eliminated, therefore substantially increasing turbine efficiency. The first was the slip loss induced by very larger lateral (to the direction of flow in rotating nozzles) separation forces (order of 6000 Earth's gravities in prior art). These very large forces separated liquid to one side of the nozzles and vapor on the other side, which results in large stream-wise acceleration of vapor while liquid being accelerated much less (i.e. the slip loss).

The second loss was due to the abruptness in flashing in prior art two-phase reaction turbines. Namely due to high over-pressurization (at pressures about 10 times higher than saturation pressure) and very short DeLaval nozzles the flashing was initiated with significant time and space delay, and then the flashing was occurring too rapidly (explosively) in an inefficient nozzle propulsion manner.

This project was clearly necessary to experimentally verify does this novel design of two-phase reaction have promise of achieving higher turbine efficiencies. Higher turbine efficiencies would mean much greater applications potential of two-phase flow turbines.

2. Project Outcome

Project outcome was favorable. We were able to accomplish number of difficult and usually expensive tasks. We have built high temperature test facility capable of producing hot saturated water at pressures of up to 334.7 PSIA and temperatures of up to 427.6 F. The test section of this facility contained the first prototype of the novel two-phase reaction turbine. The turbine rotor has diameter of 17 inches.

We were able to repeatedly safely run the turbine rotor at rotational speeds of up to 20,000 RPM, i.e. at the rotor tip speeds of up to 1480 ft/s. This is dramatic improvement over the prior art two-phase reaction turbines built and tested at the Lawrence Livermore Laboratory and at the Kobe University in Japan. The LLL's prior art reaction two-phase flow turbine was driven by fluid expansion (water flashing), which had 40% higher available isentropic enthalpy (specific energy) drop than in our test facility. The LLL turbine rotor was 16 inches in diameter and achieved top tip speeds of up to 563 ft/s.

The other major improvement was that the novel two-phase reaction turbine achieved turbine efficiencies of up to 50% while the prior art two-phase turbine, which was driven by more favorable 40% higher specific enthalpy drop, achieved turbine efficiencies of up to 33%. In other words increase in the turbine efficiency, achieved with new design, was 50% over the turbine efficiency in the prior art technology.

3. Conclusions

The significantly improved turbine efficiency of the novel design means that the novel design successfully grossly minimized some major efficiency loss mechanisms, which existed in the prior art two-phase reaction turbine. These losses were due to prior art two-phase reaction turbines having large slip loss caused by very large lateral separation forces (order of 6000 earth's gravities) acting on two-phase fluid in rotating reaction nozzles. In the novel design, the separation forces were decreased by at least factor of 100-fold; therefore the slip loss was substantially decreased as well.

The second loss was due to explosive abruptions in flashing of liquid in prior technology. Namely in the LLL rotor the liquid water was over-pressurized (over saturation pressure) by up to 1800 PSID at the entrance to very short DeLaval nozzles. Such over-pressurized liquid, and then flashed with substantial delay in an explosive, inefficient propulsion, manner. The over-pressurization is completely eliminated in the novel design. In the same time the depressurization rate was decreased by at least 100-fold, therefore avoiding abrupt flashing and associated propulsion inefficiencies.

Increased turbine efficiency, even in this small size turbine, is very significant in terms of potential for applications. The main advantage of two-phase turbines is that they are the key part of the trilateral (topping, bottoming or stand alone) thermal energy conversion cycles. Trilateral cycles or their variations are the most efficient cycles possible with so called sensitive heat resources (as the most heat resources are). Energy conversion systems that include some trilateral cycle could be as much as 50% more efficient than Rankine cycles. Many times a trilateral cycle could extract valuable mechanical work from parts of a process where such mechanical work is presently up to 100% wasted. Accordingly, placing even moderately efficient two-phase turbine in such use will be definitively quite useful in terms of increasing the overall efficiency of those energy conversion systems.

4. Recommendations

Applications recommendations:

a. Initiate first applications via cogeneration with industrial and large residential water heaters and boilers, (efficiency of conversion of the additional heat to electricity will be about 90%),

b. Initiate waste heat applications for some industries such as for example the metallurgical industry,

c. Build solar thermal energy conversion system and demonstrate its operation, (especially appropriate for two-dimensional trough solar collectors, up to 30% increase in the overall efficiency could be expected),

d. Initiate geothermal applications,

e. Use this system as bottoming cycle part of gas microturbine systems (up to 50% increase in the overall efficiency can be expected in some cases).

By carrying out this project substantial valuable experience has been gained with clear insight what can be improved in terms of turbine and test facility design as well as in early commercialization prototypes.

Some of the main **technical improvements recommendations** are:

a. Further significantly improve efficiency of the turbine by incorporating additional stage to recover the exiting kinetic energy (we have already developed novel more efficient design to accomplish this),

b. Improve the test facility so that it can provide higher specific enthalpy drop (we have observed potential of large positive effect on turbine efficiency),

c. Increase flow capacity of the test facility,

d. Special order stainless steel ball bearings with sufficient internal clearances (about 0.0025 inches) to account for difference in thermal expansion of inner and outer bearing rings,

e. Consider possible cantilevered design of the turbine rotor without lower bearing,

f. Use coaxial direct coupling between the turbine shaft and the dynamometer shaft, i.e. eliminate any transmission system.

5. Public Benefits to California

Potential benefits to California are in terms of multitude of potential applications. Some of the main potential applications are mentioned in the Item 4 above.

Solar applications perhaps have the widest potential in California. Namely it is relatively easy to use two-dimensional trough collectors and achieve temperature of thermodynamic working fluid of 400 to 500F. This is an ideal temperature for application of trilateral thermal energy conversion cycle, which would contain a two-phase turbine as its key component.

In brief, implementation of two-phase turbines in the above mentioned applications would have at least the following beneficial effects for California:

1) Reduce peak demand for electricity from the existing power generation systems,

2) Substantially increase the contribution of renewable energy (solar, geothermal etc.) to electricity generated in California,

3) Increase cogeneration of electricity,

4) Increase waste heat utilization,

5) Increase the overall efficiency of the heat to electricity conversion,

6) Decrease the air pollution and thermal pollution,

7) Increase electricity generation capacity in California without too expensive investments, i.e. decreased danger of shortage of electricity (black-outs) during peak demand,

8) Decrease the cost of electricity.

1. Introduction

1.1. Improvement due to Significantly Higher Thermal Cycle Efficiency

Thermodynamic theory of thermal energy conversion into mechanical (and electrical) energy points out to certain conditions, which maximize the conversion efficiency. One of these conditions is that the heat exchange temperature difference between a heat supplying fluid and a thermodynamic working fluid should be as small as practically possible through a heat exchanger. Temperature of most of the heat supplying fluids decreased in almost straight linear fashion as the heat (enthalpy) is taken out of that fluid in a heat exchanger. On the other hand thermodynamically the best working fluid are condensable (such as water, organic fluids, etc.) due to much smaller mechanical work needed for recompression.

These fluids need to be completely evaporated in a heat exchanger before they are supplied to a vapor turbine. This is the case in well-known Rankine cycle, which is illustrated on Figure 1a) for a geothermal binary power plant. Please note that Rankine cycles (as stand alone, bottoming, or topping cycle) are used in numerous other applications covering most of electricity generation industry. Please note that there is a large temperature difference between heat supplying fluid (geothermal brine) and thermodynamic working fluid (binary fluid). The only exception is relatively small region around so called “pinch point” where the binary fluid (liquid) is heated up to the saturation temperature and where it then starts to evaporate.

Thermodynamic analysis show that the novel thermal “binary-flash” cycle shown on Figure 1b) is appreciably more efficient even when 100% throttled flashing (no extraction of mechanical energy) is used in the topping cycle part (on Fig. 1b indicated with “two-phase turbine expansion”). When two-phase turbine is used in the topping part instead of a throttling valve then the increase in the total thermal cycle (and therefore also in the overall) efficiencies becomes significant. If that two-phase flow turbine is also significantly efficient in itself then there is a compounding effect, which makes the improvement in the overall efficiency indeed substantial.

We had calculated practical examples where increase in the overall efficiency of binary geothermal power plant was up to 40% over existing conventional binary (Rankine) plants, and up to 20% increase over the best proposed future other novel binary plants (see Figure 2). In the case of single throttling flash geothermal power plant, retrofit implantation, with reasonably efficient two-phase turbine, resulted even in 60% increase in the overall efficiency of the plant (see Figures 3 and 4).

Figure 5 compares, so called, available mechanical energies in a saturated liquid, W(0); in two-phase fluid after flashing, W(*); and in a separated vapor, W(s). Apparently the saturated liquid has by far the highest available mechanical energy. This is the reason why trilateral cycles have the highest cycle efficiencies, and why application of two-phase turbines, at least in a topping cycle, would appreciably increase the electrical power output with 100% certainty.

Just like for the application explained for the Fig. 1, use of two-phase turbine results in increase of the overall efficiency in number of other applications. Some of these other applications are: solar energy using two-dimensional trough collectors, numerous waste heat applications, cogeneration, two-phase expansion in chemical and process industry, boiler blow-downs, two-phase expansion in heat pumps, driving of our patented single cycle thermally activated heat pump, etc. There is no space inhere to explain improvement potential in these other applications of two-phase turbines.

Trilateral cycle has been discussed in number of publications. Clear analysis and brief summaries, for example, are given in References 1, and 2, from the INEEL and the City University, London. Figure 6 compares the thermal cycle efficiencies (in so called utilization efficiency form, which is also often called the Second Law efficiency) for conventional Rankine cycle and standalone trilateral (two-phase) cycle. Apparently the trilateral cycle has up to 50% higher cycle efficiency than Rankine cycle.

In standalone trilateral cycles there will be no dry steam or vapor turbines. In other words, the only device converting thermal into mechanical energy is a two-phase flow turbine or expander. Accordingly this two-phase turbine would have to have reasonably high turbine efficiencies, of 60%, per analysis from the Kobe University given in Ref. 3, in order to take sufficient advantage of higher thermal efficiency of the trilateral cycles, in such a way achieving higher overall power plant efficiency than a plant based on conventional Rankine cycle.

The enclosed Figures 1, 2, 3, 4, 5 and 6 also contain results of some worked out examples. They show that the expected improvement in the electrical power output is even up to 40% higher than for present best existing conventional geothermal power plants, and up to 20% higher than for other best proposed new improved binary power plants, with the best mixtures as the working fluid including the ammonia-steam, utilizing the same geothermal resources (Ref. 4 and 5).

Trilateral cycle power plants of either binary of brine type, as well as our two-phase flow turbine itself, are both quite simple. Accordingly this type of geothermal power plant will be also suitable for small size (up to 1 MW) off-grid village geothermal power generation systems.

Figure 7 shows that two-phase turbines can be also used in much higher temperature applications. In that case two component thermodynamic working fluid is recommended to be employed. This cycle also has its own advantages due to continuous reheat in nozzles of expanding vapor by co-flowing liquid, which has high heat capacity. We are not going in here to expand on discussion of the much higher temperature two-phase turbine applications. We consider them to be likely later on in time. Ref. 26 contains more discussion relevant to that subject.

1.2. Two-Phase Turbine Efficiencies

It was explained above that application of even poorly efficient two-phase turbines would result in appreciable increase of efficiency. Of course it would be much better if the two-phase turbine would have reasonably high turbine efficiency as well. To our knowledge the best demonstrated turbine efficiency of two-phase turbines is 54% as achieved by 700kW turbine at Wakamtsu in Japan, which was built by Kobe Steel Co. per research done at the Kobe University. This turbine is used to generate electricity from waste heat from a Steel Mill. Two-phase water is used as the working fluid. The turbine is of 100% impulse type, and we understand that erosion of the turbine blades is a serious problem.

It is our understanding that the LLL two-phase reaction 25kW turbine had the highest demonstrated turbine efficiency of 33%. The LLL projected that turbine of their design in 1MW size would have turbine efficiency of up to 50%.

Design of our novel two-phase reaction turbine greatly minimizes two main loss mechanisms from the prior art technology turbine, which was build and tested at the LLL. In addition we have superior mechanical design of the turbine rotor. Figures 8, 9 and 10 and Tables 1 and 2 summarize and explain the improvements accomplished by our design of the turbine rotor. More extensive explanations are given in References 17 and 18.

The better mechanical design and better fluid dynamic design enabled us to run our turbine at the rotor tip speeds up 1480 ft/s, which is 2.6 times higher than the tip speeds achieved in the LLL experiments. This is very remarkable achievement considering that the mechanical tension stresses in the rotor are proportional to a square of the tip speeds, and that the driving fluid in the LLL experiments had 40% higher enthalpy drop.

Based on measured turbine efficiencies of up to 50% of the novel turbine in size of 25kW projections can be made about future performance potential. The projection is that in 1MW size the turbine efficiencies would be in excess of 60%. In addition, introduction of some design improvements, for example recovering of the discharge kinetic energy, would increase the turbine efficiency up to 70% and perhaps even higher.

We should mention that two-phase fluid dynamic and initiation of flashing in reaction turbines is extremely complex. There are no available computer modeling codes, which could in advance predict performance of such new turbines. Even if one would write (which is a monumental task) such a code now, it (the code) would have to initially completely rely on experimental data. At the best what such could predict would be trends of change. For instance, if experimental data are available for a certain turbine test, then the code could predict very roughly what would be a change trend for turbine performance for relatively small off-design change of the test parameters.

We have extensive R&D background in fluid dynamics of single-phase and two-phase flows including their computation modeling. We also had communications about this subject with Professor Clayton Crowe who wrote a textbook on computer modeling of two-phase flows (Ref. 59), and who was part of the team involved in R&D on two-phase flow reaction turbine at the LLL. He fully agrees that two-phase flow modeling can only forecast trends and cannot forecast actual results.

2. Project Objectives

The Project Objectives were the following;

- build two-phase turbine test facility capable of heating water up to 435F and 350PSIG, and testing two-phase turbine,

- build first 25kW prototype of novel two-phase reaction turbine,

- test the turbine prototype.

All the above very challenging objectives have been fully accomplished.

3. Project Approach

3.1. Test Facility

Schematic of the test facility is shown on Figure 11. Boiler/ water heater heats the water, which is kept under pressure in a liquid state up to 435F and 350PSIG. This water is stored in 200 gallons accumulation tank. This water later on is pressurized by gaseous nitrogen and forced to flow into the two-phase turbine.

The two-phase turbine is mounted as the top dome part of the separation tank. The separation thank has volume of 380 gallons. The steam is exhausted during the tests, from the separation tank to outside of the building. The liquid water (at temperature of about 215F) is retained in the separation tank and is later on returned into the accumulation tank and the water heater.

Schematic of the turbine assembly with chain transmission and a military aircraft three-phase electrical generator are given on Figure 12. The operational speed of this electrical generator is 6000 RPM. Transmission gears down the turbine speed of 20,000 RPM to generator speed of 6000 RPM. The electrical output from the three-phase generator was taken to a load consisting of three balanced resistors, which were cooled using high velocity industrial grade fan.

The rotor of the turbine prototype was made of ferritic stainless steel of high tensile strength. The rotor and the shaft were designed in such a way to be able to withstand high rotational speeds and to reasonably decrease the highest tensile stresses, which occur near the center of rotation. This was the reason why we were able to safely run our turbine rotor at 2.6 times higher tip speeds than in the prior art technology.

There are many mechanical and electrical design features and experiences learned about the test facility and the test turbine prototype. It would take too many pages to describe them, and most likely it would not be of immediate interest to readers of this report.

One of most difficult problems, which we encountered, was with ball bearings at all three locations on the shaft (later on we have added third ball bearing just below the small sprocket at the top of the turbine shaft). The problem was caused by the fact that our shaft was heated up to temperatures of 400F by hot water entering it from below. This meant that the inner rings of the bearings were also heated up to temperatures close to 400F. The outer rings of the bearings remain on temperatures, which were by 150F to 200F lower. This caused higher thermal expansion of the inner bearing ring than of the outer ring. This difference in the expansion caused closing of the inner clearance for the running track of the ball bearing during number of runs. In number of tests the available inner clearance was completely closed by this difference in the thermal expansion of the bearing rings.

The above problem caused sudden jamming of the bearings, during very high speed runs, perhaps as many as twenty times. One time, due to jamming of the bearing just about the rotor, the shaft was exposed to very severe thermal shock, which caused the shaft to completely break (at a location adjacent to the thermal shock) due to internal thermal stresses. The problem was that the bearing manufacturers do not readily offer ball bearings for 400F with sufficient internal clearance. The manufacturers told us that they would make such bearings for us if we would order 500 of such bearings at the cost of $15,000. In retrospective this would have been worth ordering. We did give number of existing high temperature stainless steel bearings to high precision grinding company in order to increase the inner clearance by 0.001 inches. However they were not able to take the existing stainless steel bearing non-destructively apart due to existence of the cage runners and absence of demounting groves for the balls.

For most of the test runs we have used ball bearings made of chromium steel with C3 internal clearances. (Stainless steel bearings are not readily available in C3 internal clearance). Their size of clearance (C3 for chromium steel) was marginal, i.e. some of them would jam while the other would not. The chromium steel also rusts in the steam atmosphere existing in our turbine. Would also took care to lubricate these bearings immediately before and after the tests. We used special aviation lubrication engine oil, which is stable up to temperatures of 700F. The chromium steel bearings had to be replaced quite often due to rusting.

During heating of the water it was circulated slowly between the heater and the accumulation tank. The circulation was needed in order to prevent burning of the heater pipes, which could occur due to too slow removal of the generated steam in the pipes. There was safety electrical interlock, which automatically turned off the heating if the pump stopped to rotate. The pump was purchased from a German company, Speck Pump. Hercules Power Equipment Co. made the water heater where the experiment was located.

Initially we had serious problems with jamming of shaft of the pump caused by small tolerances in the magnetic drive coupling of the pump. Speck Pump Co. asked us to return the pump for an overhaul. We did not have time for it; instead we were able to successfully fix the pump coupling ourselves.

On the very top of the turbine shaft a small stainless steel black and white “target” disc was mounted. The target was used to optically measure RPM-s of the turbine rotor. This measurement turned out to be very reliable and accurate in most cases. We have checked the accuracy of this reading by also measuring the frequency of the electricity output from the electrical generator (turbine to generator transmission ratio was 3.33).

Turbine power output was measured via measuring the electrical power dissipated on the three-phase electrical load. Transfer efficiency coefficients for the chain transmission of 0.85 and for the electrical generator of 0.85 were used. These are reasonable efficiency coefficients considering large radial forces existing in the six ball bearings, continues wear on both sprockets, continuous seizing between chain link members, age of the generator, etc. Seizing of the chain was reduced by continues dripping lubrication by oil on one of the sprockets.

Figure 15 is a photograph of part of the high temperature test facility (reader should refer to Figures 11 and 12 for the complete facility). The text under the Figure 15 explains the key components on the photograph. Figures 16 and 17 are photographs of the high temperature high pressure water heater (boiler). This water heater was custom made for us by the Hercules Power Equipment Co. Delayed completion and delivery of this water heater was one of the main factors contributing to late finalization of this project.

3.2. Turbine Prototype

The most important feature of our new-patented turbine is novel proprietary design of its rotating reaction nozzles. In the prior art two-phase reaction turbines hot saturated water was introduces into the rotor through a hollow shaft. In our turbine the water is introduced into the rotor in exactly the same way, but the rotating reaction nozzles are very different.

We have already mentioned that the rotor of our turbine had superior mechanical design enabling it to run at substantially higher speeds. This is important for the fluid dynamic energy conversion turbine efficiency as well. Reaction turbines usually do achieve higher efficiencies at velocities that are about 2.5 times higher than for impulse turbines.

The main improvement was novel fluid dynamic design of the key rotating reaction nozzles. They have two substantial advantages over the prior art technology. First, the separation forces (acting laterally to streamwise directions in the nozzles) were dramatically reduced. Reduction of the separation forces greatly reduces the slip loss. In the prior art turbine at the LLL these forces were of the order of being 6000 times larger than the Earth’s gravitational forces (i.e. than the usual weight of the water).

This large reduction in the separation force is achieved by proprietary curving of the nozzles. The curve determining equations are the most extensively explained in our patent (Ref. 17) and in the recommendation report (Ref. 18) issued by the National Institute of Standards and Technology. (The NIST carefully reviews the energy inventions under the Energy Related Inventions Program, and then recommends only 2% of them, and then issues a report on each one of the recommended innovations only). The curving is calculated in such a way that all lateral forces on the fluid balances out to zero. In practice these lateral forces would not balance out to zero, but we estimate that the lateral resultant force (i.e. sum) would be reduced by factor of 100 fold or better. This reduction would then result in large decrease in the slip loss.

The second large improvement is drastic reduction in abruptness of flashing, which is also explained in Ref. 17 and 18). Namely, in the prior art technology the rotating DeLaval nozzles were very short and were placed completely (i.e. whole nozzles) at the outer perimeter of the rotor. Calculations show that at the rotational speed of 8066 RPM the water at the very entrance to the nozzles was at the pressure about 1800 PSID higher that the saturation pressure. Such water does not contain so called "nucleation sites" (tinny bubbles) which are needed for un-delayed initiation of flashing (i.e. rapid development of larger steam bubbles).

Passing highly over-pressurized water through very short DeLaval nozzles, as was done in prior art, results in delay of flashing and then in explosive flashing. Such flashing is inefficient in terms of nozzle reaction forces.

Novel design practically completely avoids the abrupt flashing. First of all, new DeLaval nozzles start close to the centerline of the rotor. This means that at the nozzle entrance the pressure is not much higher than the saturation pressure (which is the pressure at the center of the rotor). Second, the cross-section of the nozzles changes very gradually along the nozzles. This means that the de-pressurization and the flashing is much more gradual. In our estimation the de-pressurization rate is decreased by factor of 1000. In such a way abruptness and inefficiency in flashing is avoided.

Table 1 summarizes analysis of lateral forces on fluid in the rotating reaction nozzles in the prior art technology and in our novel turbine. Table 2 summarizes analysis of abruptness in flashing in the rotating reaction nozzles in the prior art technology and the in our novel turbine.

Photographs of the turbine rotor including its semi-hollow shaft are given on Figures 13 and 14. The rotor and the shaft were machined from high tensile strength ferritic stainless steel. Curved nozzles were machined by numerically control tool machines. Machining computer program (software) was generated from our own nozzle design computer program.

3.3. Testing

The testing was done in the following manner. The accumulation tank and the water heater were filled with water. The water was circulated with a pump during the heating. Once the desired temperature and pressure of water was reached the heater was turned off, or was left on (usually at reduced rate of heating) in order to provide additional pressure for avoiding flashing of water before it reached the turbine.

Flow rate was measured using turbine flow meter from Omega Engineering. Care was taken to ensure that the water was completely in the liquid state at the flow meter.

Temperatures and pressures were measured upstream and downstream of the flow control valve. The final flow control valve was 2-inch ball valve because it offers very low flow resistance.

Test runs were always started at low flow rates for few minutes. The reason was to give time to the supply piping, turbine rotor, and bearings to get heated to close to the operation test temperatures. After that the flow rate was raised slowly over couple of minutes to the test flow rate. Next we would wait until the turbine would reach steady high speeds.

Once the steady state was reached test data was taken. The test data consisted of pressures and temperatures upstream and downstream of the flow control valve and downstream of the turbine, flow rate, rotational speed, and electrical power output.

Due to high-pressure drop caused by flashing in supply pipe we have changed that pipe from 1 to 2 inches all the way almost to the very entrance into the turbine as explained further below.

4. Project Outcomes

4.1. Building of the Test Facility

Building of this kind of a test facility is difficult and ordinarily expensive task. We have used maximum ingenuity and sacrifice to be able to accomplish this project at a reasonable cost. The real cost was appreciably higher than funds received from governmental agencies, and higher than in advanced projected “book value” of the project. We have absorbed the significant extra costs, however they were not extraordinary high as they could have been normally expected to be based on “market” rates of this type of project. For example two specialized companies asked us in excess of $80,000 just for a high-speed dynamometer. We were able to save and use electrical generator from a decommissioned military aircraft as dynamometer (such new electric generator costs about $80,000). This is just one example of the savings accomplished.

There were also cost saving solutions with some other key pieces of equipment, for instance with high temperature high-pressure water heater. We have designed and build blow-down test facility because continuously running facility is considerably more expensive.

Later on we have made some improvements to the test facility in order to improve the testing capabilities. The most significant improvement (resulting in very good results) was that we have changed major part of the pipe going from the high temperature high pressure tank all the way to the very entrance of to the turbine. Initial one-inch pipe was changed to two-inch pipe. In addition one-inch needle type control valve and one-inch globe type safety electrically operated valve were replaced by two-inch ball valves. In this way there was drastic reduction in the pressure drop upstream of the turbine. This pressure drop was decreased from as high as 150 PSID down to bellow 10 PSID. This was very important in terms of providing more driving power to the turbine rotor. Even more importantly the goal was to avoid any two-phase flashing upstream of the turbine rotor.

Inlet pressure and temperature were measured eight inches upstream of the entrance to the turbine rotor. The pressure and temperature were also measured in the two-inch pipe just upstream of the two-inch ball control valve. Exiting temperature was measured in the separation tank. The exit pressure was measured in the entrance part of the steam exhaust pipe. The highest accuracy pressure gauges and temperature thermistors were used to perform the measurement.

The flow rate was measured in the supply pipe upstream of the control ball valve. High precision turbine flow meter was used for this purpose. The highest care was exercised in order to make sure that the fluid (hot pressurized water) is completely in the liquid state at the turbine flow meter. Any test where this was in any doubt was rejected.

Measurement of the power output was mentioned earlier. There were also electrical safety circuits to protect against overspeed of the turbine, over-current, and over-voltage in the electrical generator. This military aircraft electrical generator is normally excited by 40 V current. We have changed this and make the exciting current of variable voltage. In such a way we were able to change power output, i.e. change loading on the turbine, without changing load resistance. In this way we did not have to buy expensive load bank resistors (about $8,000).

4.2. Turbine Prototype Outcome

Turbine was successfully built per our design and drawings. Design speed of the turbine was 20,000 RPM. Material yield stress would allow the turbine to run up to approximately 50,000 RPM. The turbine was run number of times in unloaded and loaded conditions at 20,000 RPM.

4.3. Turbine Testing Outcome

The outcome of testing of the turbine is given in Table 3. Figure 18 displays the turbine efficiency as function of the rotational speed. Apparently higher speeds have positive effect on the turbine efficiency. Our turbine design speed, both mechanically and fluid dynamically, was at 20,000 RPM. At that turbine speed the electrical generator rotated at 6000 RPM, which was its design speed. Accordingly we exerted great care not to exceed turbine speed of 20,000 RPM.

Further discussion of the testing outcome is given in the next section below.

5. Conclusions

The test results show that this novel two-phase reaction turbine is about 50% more efficient than the prior art technology two-phase reaction turbine of almost the same rotor diameter which was tested with 40% higher specific enthalpy drop of the driving fluid. Significantly, our test results indicate that increasing the driving specific enthalpy drop has appreciable positive effect on the performance of the turbine. In other words if our test facility was capable of delivering 40% higher specific enthalpy drop then it was likely that our turbine might have achieved the turbine efficiency of about 55%.

The above test results prove that novel two-phase reaction turbine can have appreciable high turbine efficiencies even in small sizes (25kW) and even without recovering the exiting kinetic energy. It is our estimation that recovering the fluid's exiting kinetic would increase the turbine efficiency by additional 10 to 15 percentage points. In other words this additional improvement would raise the efficiency of a small (order of 25kW) two-phase turbine up to 60 to 65%. This is impressive turbine efficiency for this type of device considering that there are presently small (150kW) single-phase steam turbines for sale with the turbine efficiencies of 45%.

Increasing size of two-phase turbine (which includes recovery of the exiting kinetic energy) to about 1 MW would likely result in the turbine efficiencies of 70 to 75%. This would be very acceptable efficiency, which would greatly increase practical applications of two-phase turbines making these applications useful and economical.

While reading the above discussions and the two-phase turbine efficiency projections one also has to have in mind great thermodynamic advantages of the trilateral thermal (topping, bottoming or standalone) cycles. Namely, the trilateral cycles are thermodynamically most efficient thermal cycles possible in most of practical energy conversion applications. In many cases trilateral cycle can extract mechanical energy from thermal parts of conversion systems where presently the "availability" is completely or mostly wasted. In these cases addition of a trilateral cycle would result in appreciable increase in the electrical power output even if two-phase turbine has poor turbine efficiency, but use of efficient two-phase turbine does further improves the economics (i.e. CEO) substantially.

6. Recommendations

6.1. Improve Further the Turbine Prototype and the Test Facility

In our tests the fluid was leaving the turbine rotor still containing considerable kinetic energy. Major part of that kinetic energy can be recovered, i.e. converted into additional useful turbine shaft energy output. There are few known and tried and proven methods of recovering the kinetic energy of high velocity fluid. We also already have our own design, which we believe would more efficiently recover the exiting kinetic energy in our particular turbine. Incorporation of a novel stage of recovering the exiting kinetic energy in our turbine would also decrease the optimal operating speed of the turbine from present 20,000 RPM to about 10,000 RPM. It is significant that a dynamometer for the speed of 10,000 RPM costs about $20,000, while for speed of 20,000 RPM it costs about $80,000.

Accordingly we recommend improving the design of our turbine by incorporating additional stage which would recover most of the presently mechanically wasted (efficiency-wise) the exiting kinetic energy of the fluid. It is our estimation that such small turbine (size of 25 kW) tested in the present test facility would reach turbine efficiency of 60%

We have also observed from the test results that the turbine efficiency would increase with further increase in the driving fluid's specific enthalpy drop. Accordingly we recommend purchasing 400 gallons (instead of present 200 gallons) hot water accumulation tank which would be able to operate at 800 PSIA and 520 F (instead of present 365 PSIA and 435 F). In this way the driving specific enthalpy drop would be increased by more than 100%. To run similar power output tests about half of the fluid flow rate (compared to present flow rate) would be sufficient. The outcome would be four times longer test runs. The most importantly it is expected that the turbine efficiency would increase as well.

The test facility should be further improved. One of the most important improvements should be use of dynamometer to measure the mechanic power output from the turbine. In this case the coupling of turbine shaft and the dynamometer shaft would be direct and coaxial (probably spline type coupling). In this ways instead of present six ball bearings (three on turbine shaft and three on electric generator shaft), which were exposed, to large radial forces, there will be only two ball bearings, which will be exposed to much smaller radial forces.

Next we should special order in advance stainless steel high temperature ball bearings with larger internal clearances for running of the balls. Namely readily available stainless steel ball bearings have so called C-0 internal clearances, i.e. the internal clearances of only 0.0005 inches.

It is exacted that the increase in the driving specific enthalpy drop, plus recovering of the exiting kinetic energy of the fluid would result in the turbine efficiency of these small (25 kW) two-phase reaction turbines of about 65%.

6.2. Initiation of Commercialization Recommendation

6.2.1. With completion of these tests and this report, determined efforts should be made to initiate commercialization of this technology. The first target market should be cogeneration in conjunction with industrial, commercial and large residential boilers and water heaters. Namely water from existing boiler or water heaters would be heated (in an additional heater) to a higher temperature and pressure. Such water would be then flashed through a reaction two-phase flow turbine down to the temperature of the original water heater where this hot water would be used.

In the above cogeneration application about 90 to 95% of the additional heat (supplied to the additional water heater) would be converted into electricity. This represents well-known efficiency and economics advantage of generation of electricity via cogeneration. Production of electricity via cogeneration usually has about 50% lower cost of electricity (COE).

In order to initiate this first applications of small two-phase flow turbines it is recommended to make a commercial type prototype of more or less complete electricity-generating system.

6.2.2. Second projected market for this technology is generation of electricity using two-dimensional solar trough collectors. Such collectors can be placed in many locations on flat roofs of larger buildings or, outside of the cities, on the ground. Such collectors can heat the thermodynamic working fluid to temperatures of 400 to 600 F. This is ideal temperature for application of topping or standalone trilateral thermal energy cycles where an efficient two-phase turbine would be the key component. We have mentioned earlier that the trilateral cycles would be 20 to 40% more efficient than presently used thermal cycles.

We recommend design and building of a commercial type prototype of solar to electricity conversion system.

6.2.3. There are number of other potential markets. One of them is for geothermal power plants. In this case two-phase turbines of sizes of 500 kW and larger will be necessary. It is our recommendation that 500 kW or larger two-phase flow turbine should be installed in a geothermal power plant

7. Public Benefits to California

California would especially benefit from applications of this technology, due to its large availability of solar thermal energy, high availability of geothermal energy, and large industrial and residential base where there are numerous opportunities for cogeneration of electricity.

Two-phase turbines are especially amenable for distributed small-scale generation of electricity. It is generally projected that there will be large increase in the distributed electricity generation in California.

It is next to impossible to realistically predict rate of market penetration of new technology. However two-phase turbines as part of trilateral (topping, bottoming and standalone) thermal cycles could, on the average, increase the overall conversion efficiency in many applications in practice by about 25%. This would make its applications attractive.

We can conservatively assume that progressively each year about 0.5% more of California electricity will be produced employing systems, which will include two-phase flow turbines. Based on present California's annual electricity consumption rate of 274,000 GWh, 0.5% is 1,370 GWh. Assuming further that the this equipment would produce electricity only 3,000 hours per year we get the yearly increase in California electricity production capacity (solely via two-phase turbines) of 457 MW per year.

We can guesstimate that an average capital cost of building trilateral cycle two-phase turbine energy conversion system would be about $300/kW. Accordingly building this specific annual additional capacity in California would cost 1.37 billion dollars per year.

Assume that after 10 years 5% of California electricity needs are provided by two-phase turbine systems. This would be amount of 13,700 GWh. Average consumer cost of an incremental kWh is 30 cents. Accordingly value of the producing incremental 13,700 GWh per year would be 4.11 billion of dollars per year. If this additional electrical energy is produced at 20% higher conversion efficiency then it is equivalent to getting 20% of such generated electricity (2,740 GWh per year in California) for “free”. Using the rate of 30 cents per incremental kWh the annual saving in California is 0.82 billion dollars.

8. Development Stage Assessment

The Stages and Gates Process of the California Energy Commission has the following Activities for the Stage 3, Research and Bench Scale Testing:

8.1. Marketing. We have become well familiar with potential applications and the markets for this technology. Our preliminary marketing attempts had to be stopped due to clear need to have demonstration prototype first. We intend to devote more time to this important issue in the near future. Help from the California Energy Commission and the U. S. Department of Energy would go a long way to successfully initiate commercialization.

8.2. Engineering/Technical. Engineering and technical work of design building of the test turbine prototype and the test facility was successfully carried out. Turbine rotor tip velocities 2.6 times higher than in prior two-phase reaction turbines have been achieved. Turbine efficiencies up to 50% higher than in prior two-phase reaction turbines have been achieved.

8.3. Legal/Contractual. The patent is held by Dr. Fabris. He also holds another patent on a single cycle thermally activated heat pump, which used the subject two-phase reaction turbine as its key driving component. There are no patenting issues to be resolved.

8.4. Risk Assessment/ Quality Plans. We believe that there is no significant technological risks for this technology considering that significantly higher turbine efficiencies and the rotor tip speeds have been demonstrated. Quality Plans have not been developed at this time.

8.5. Strategic. This technology has no critical dependence on other projects under development by PIER or elsewhere.

8.6. Production Readiness/ Commercialization. There have been no disclosures of the project results to potential manufacturers. There is no production readiness plan and no “should cost” estimates.

8.7. Public Benefits. Some of potential Public Benefits are:

- Reduced environmental impact due to use of renewable heat resources such as geothermal, solar, also due to increased cogeneration, increased efficiencies (via implementation of trilateral cycles), waste heat utilization, etc.
- Increased implementation of distributed power generation,
- Increased reliability of the California electricity system,
- Increased affordability of electricity in California.

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TABLE 3: PERFORMANCE DATA

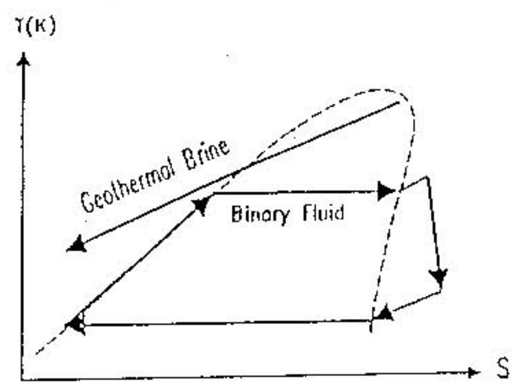
Test No.	Inlet Conditions Temp. [F]	Pressure [PSIA]	Flow Rate [lb/s]	Case Pressure [PSIA]	Turbine Speed [RPM]	Shaft Power [kW]	Turb. Effic. [%]
1	351.4	142.5	2.20	17.35	11,400	8.72	31.3
2	358.7	155.4	2.40	17.64	12,500	11.51	34.7
3	365.0	166.4	2.48	17.78	13,700	13.80	37.4
4	371.4	182.6	2.45	17.75	15,100	16.14	40.9
5	380.9	206.10	2.41	17.59	17,400	20.22	45.4
6	388.2	224.7	2.44	17.69	19,300	23.38	48.1
7	401.1	255.3	2.11	17.20	19,500	24.47	49.4
8	409.8	279.8	1.93	16.90	19,800	24.95	50.1

TABLE 1: ANALYSIS OF LATERAL FORCES IN ROTATING TWO-PHASE NOZZLES. (MUCH LESS SEPARATION IN NEW NOZZLES)

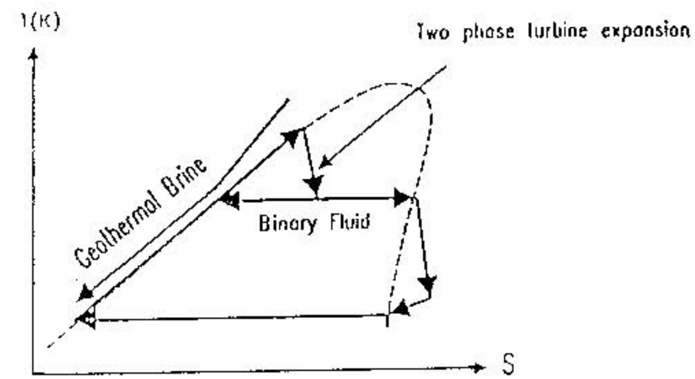
FACTS	LLL TURBINE	TURBINE INVENTED BY DR. FABRIS
1) AXIS OF ROTATING NOZZLES	TWO STRAIGHT PIECES	APPROPRIATELY CURVED TO CANCEL OUT LATERAL SEPARATION FORCES
2) CROSS-SECTIONAL SHAPE OF NOZZLES	THREE FOLD ABRUPT ENLARGEMENT AT THE TROAT	NORMAL DELAVAL CROSS-SECTIONAL AREAS
3) MAGNITUDE OF LATERAL FORCES(CENTRIFUGAL AND CORIOLIS) SEPARATING TWO PHASES IN THE HIGHLY ACCELERATING NOZZLE FLOW	ON AVERAGE 6000 TIMES LARGER THAN GRAVITATIONAL WEIGHT OF LIQUID	ON AVERAGE LESS THAN 50 TIMES WEIGHT OF LIQUID
4) LATERAL MEAN LOCATION OF TWO PHASES	ON AVERAGE LARGELY SEPARATED	ON AVERAGE THE SAME (HOMOGENEOUS)
5) EFFECTS ON STREAMWISE ACCELERATION OF FLUID	LARGE STREAMWISE VELOCITY SLIP BETWEEN TWO PHASES	MUCH LOWER VELOCITY SLIP BETWEEN TWO PHASES
6) SLIP LOSS IN NOZZLE EFFICIENCY	30%	4%

TABLE II: ANALYSIS OF FLASHING ABRUPTNESS IN ROTATING TWO-PHASE NOZZLES. (MUCH LESS ABRUPTNESS IN NEW NOZZLES)

FACTS	LLL TURBINE	TURBINE INVENTED BY DR. FABRIS
1) $(P-P_{sat})$ AT THE NOZZLE ENTRANCE DUE TO CENTRIFUGAL FORCES IN ROTATING UPSTREAM PASSAGES	$10 * P_{sat}$	$\sim 0.1 * P_{sat}$
2) LENGTH OF THE CONVERGING PART OF THE NOZZLE	0.05 R	0.3 R
3) NUCLEATION SITES(TINY BUBBLES) IN LIQUID NEEDED TO INITIATE FLASHING	ABSENT(DISSOLVED)	PRESENT
4)LIQUID DEPRESSURIZATION RATE	100000 $[P_{sat}/s]$	100 $[P_{sat}/s]$
5) INITIAL LOCATION OF FLASHING	COUPLE OF INCHES DOWNSTREAM OF THE TROAT	UPSTREAM OF THE TROAT
6) FLASHING DYNAMICS	ABRUPT, EXPLOSIVE, TOO FAR DOWNSTREAM OF EQUILIBRIUM LOCATIONS	GRADUAL, CLOSE TO PROPER EQUILIBRIUM LOCATIONS
7) EFFECT ON NOZZLE EFFICIENCY	INEFFICIENT REACTIVE PROPULSION	EFFICIENT REACTIVE PROPULSION
8) QUANTITATIVE LOSS IN NOZZLE EFFICIENCY	30%	3%



a) Conventional Existing Binary (Rankine) Geothermal Power Plant Cycle



b) Novel More Efficient Flash-Binary Geothermal Plant Cycle

Figure 1. Thermodynamic Diagrams for Binary (Rankine) and for Binary-Flash Energy Conversion Cycles (If binary-flash cycle employs only two-phase throttling valve it is still appreciably more efficient than conventional binary plants. Employing efficient two-phase turbine increases the efficiency of this cycle even more, i.e. up to 40% higher than of conventional binary plants.

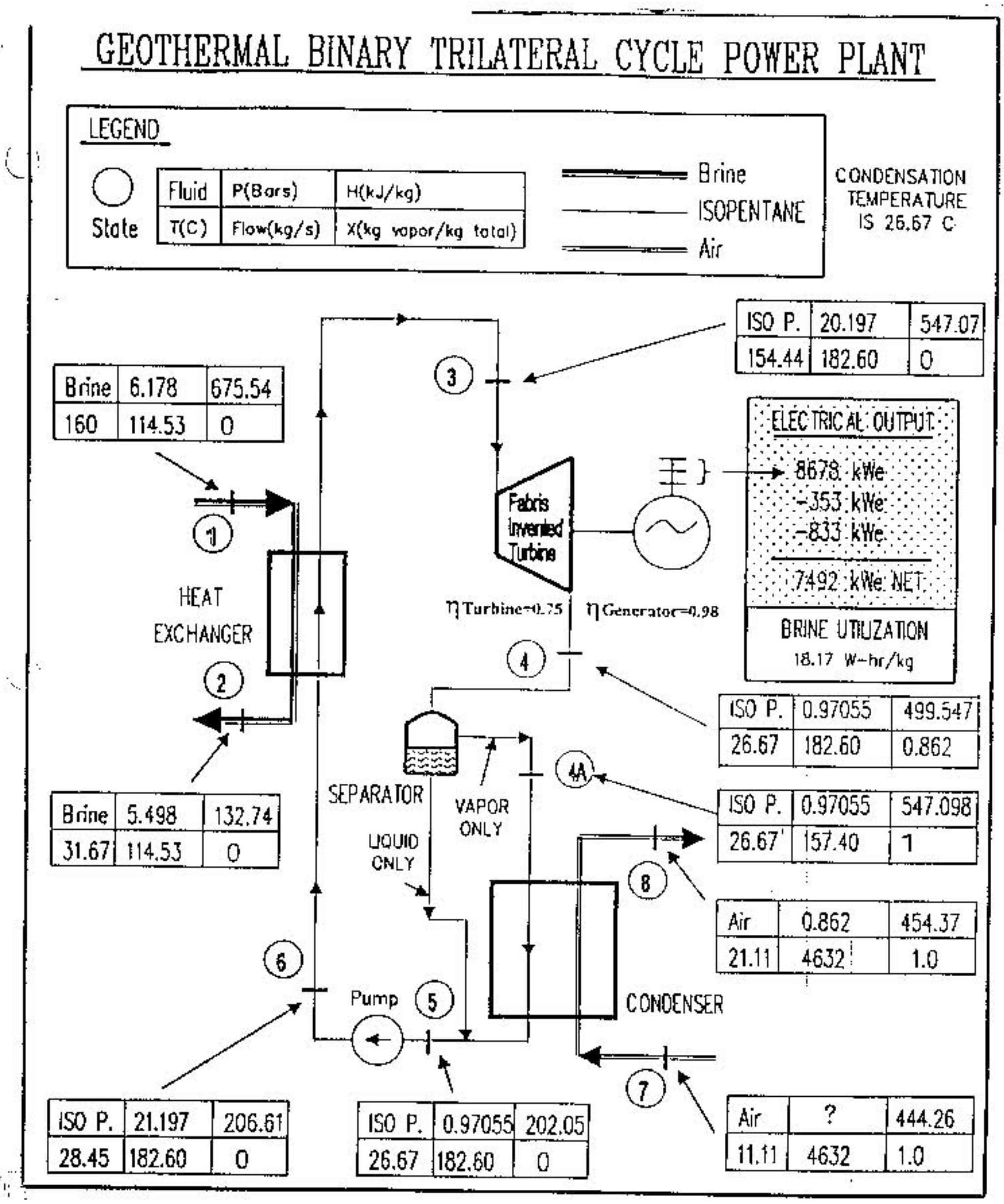
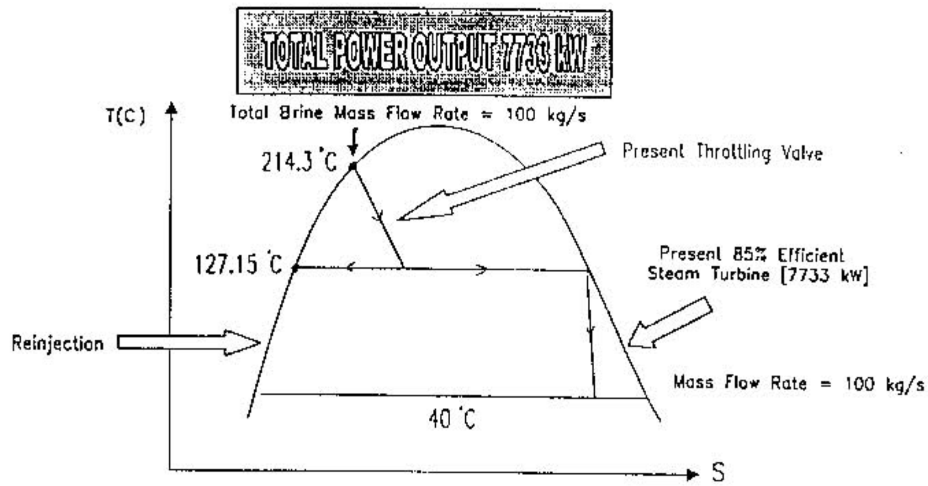
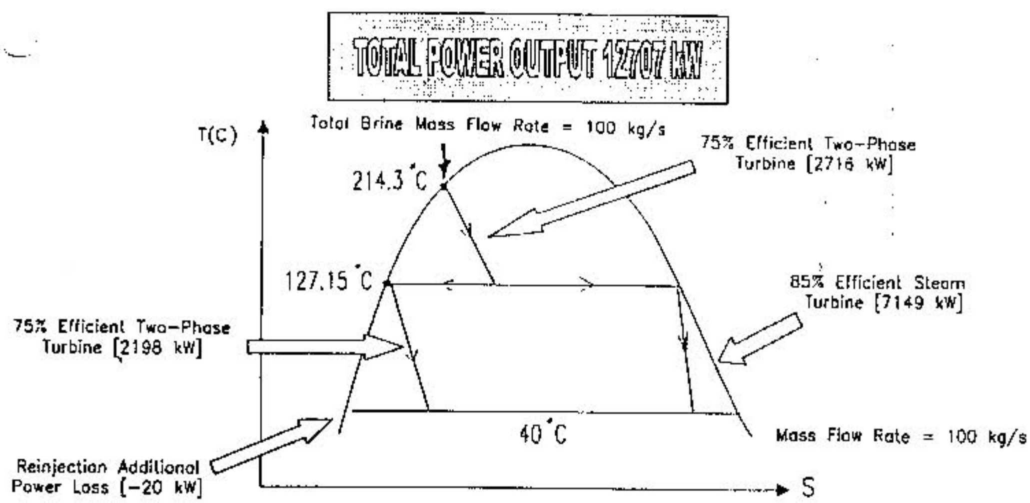


Figure 2. Geothermal Trilateral Isopentane Cycle Power Plant Employing Efficient Two-Phase Turbine (Improvement of over 40% over existing and of 20% over other best proposed binary plants)

PRESENT SINGLE FLASH GEOTHERMAL PLANT



PROPOSED RETROFITTED GEOTHERMAL PLANT



Figures 3 and 4. Present Single Flash and Proposed Retrofitted Geothermal Plant (Output increased by over 60%)

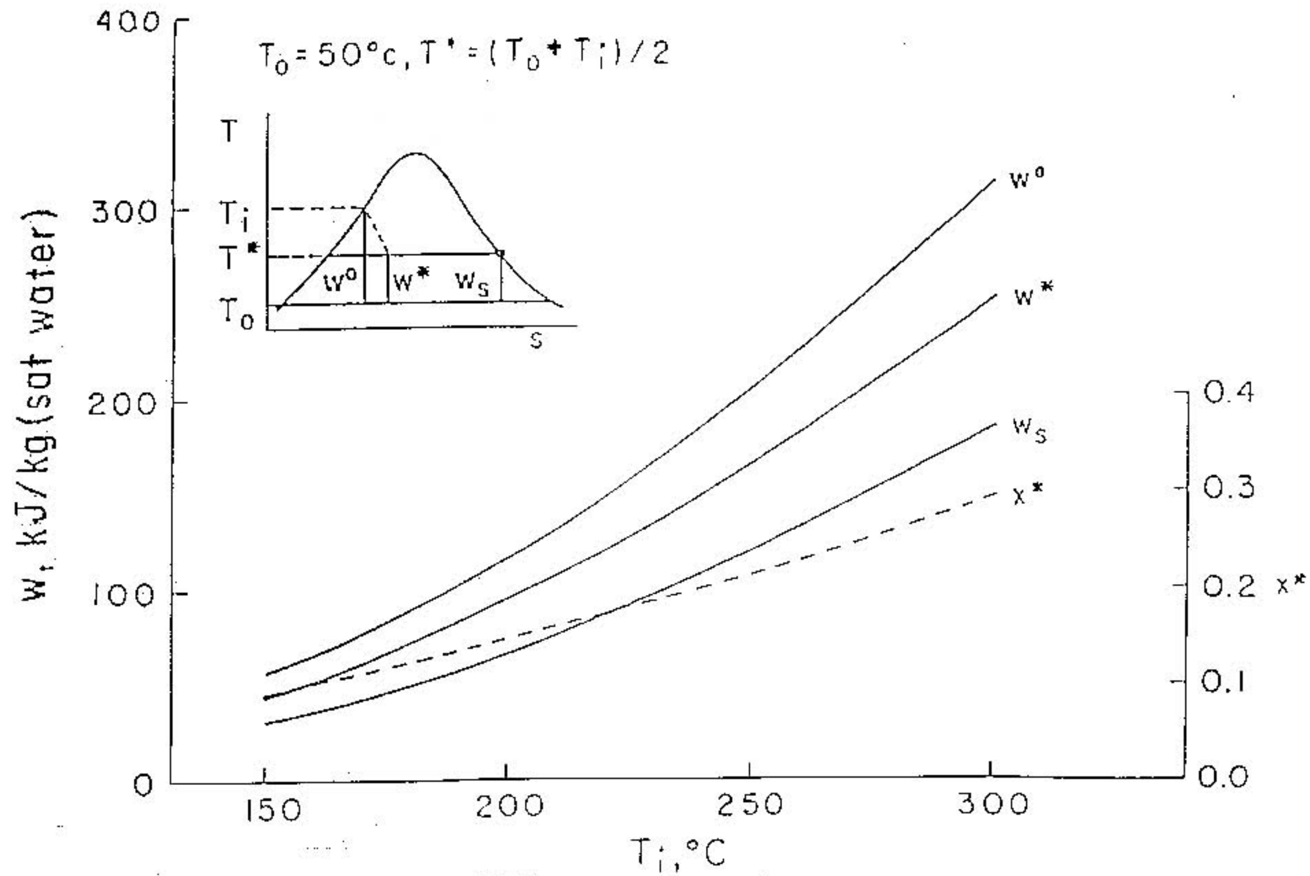


Figure 5. Available Mechanical Energies: W(0) – in saturated liquid, W(*) – in flashed unsepartated two-phase fluid, W(s) – in separated vapor, (large amount of available mechanical energy is wasted by throttling).

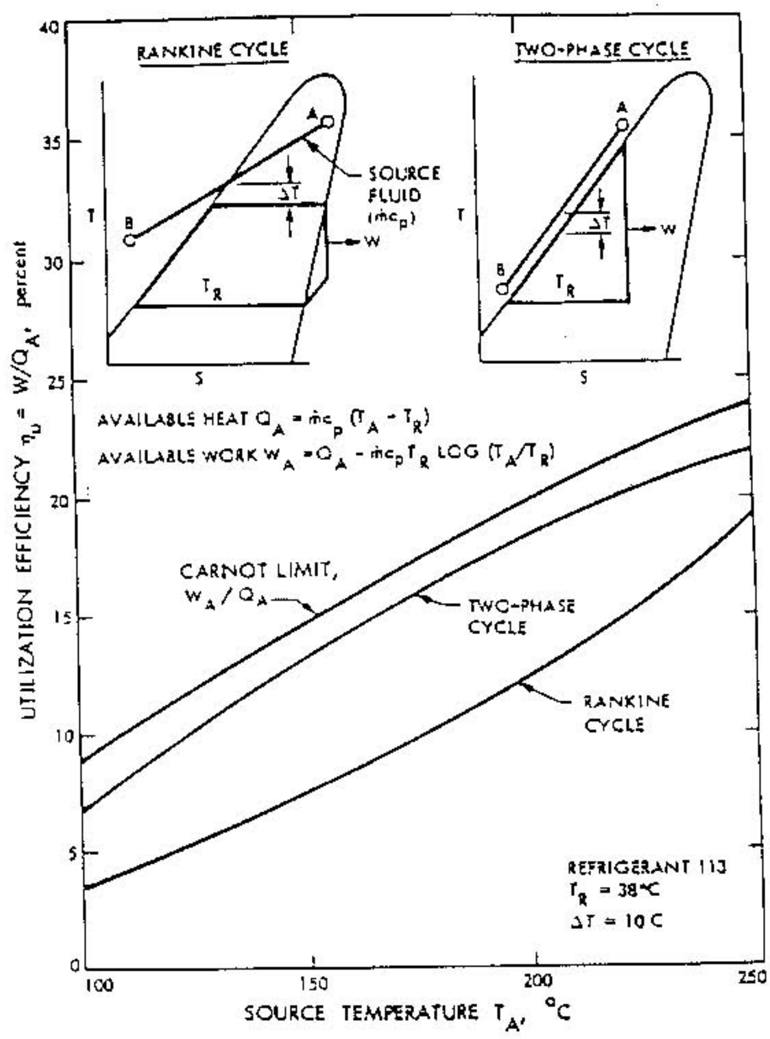


Figure 6. Comparison of Rankine and Organic Two-Phase Turbine (Trilateral) Cycles (Potential increase in the thermal cycle energy conversion efficiency is up to 50%).

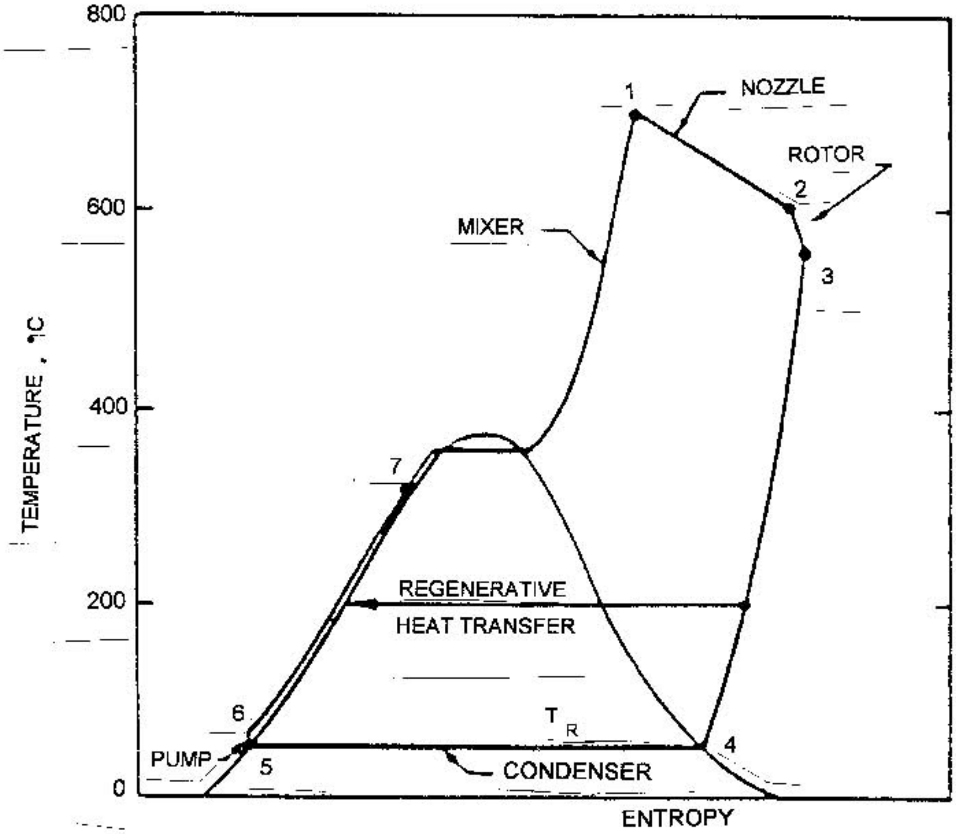


Figure 7. T-s Diagram for Thermodynamic Working Fluid of Two Component Two-Phase Turbine Cycle (for potential high temperature applications achieving higher thermal cycle efficiencies).

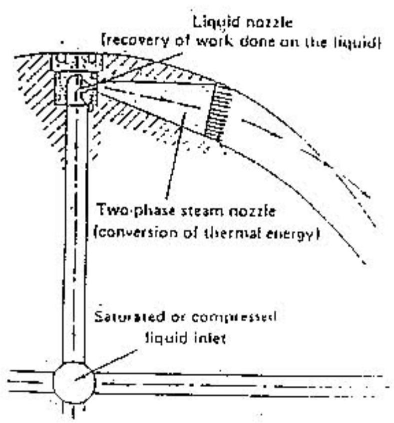
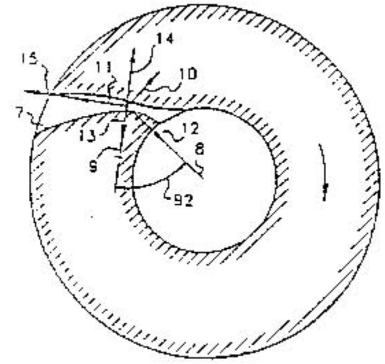


Figure 8a) Prior Art Two-Phase Rotor Tested at LLL;



12 - Centripetal Acceleration due to Transfer Motion (Rotation)
13 - Centripetal Acceleration due to curving of relative motion of fluid with respect to rotor
14 - Coriolis Acceleration
11 - Streamwise velocity
15 - Streamwise Acceleration
10 - Local Velocity of the Rotor
9 - Local Radius of curvature of the Nozzle
8 - Local Radius of the Rotor
92 - Angle between two radii

Figure 8b) Acceleration & Velocities in Rotating Nozzles;

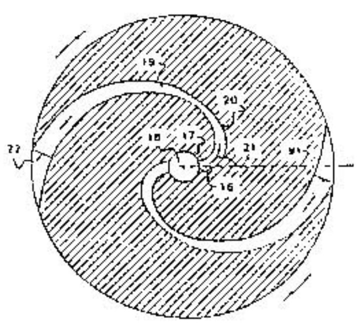
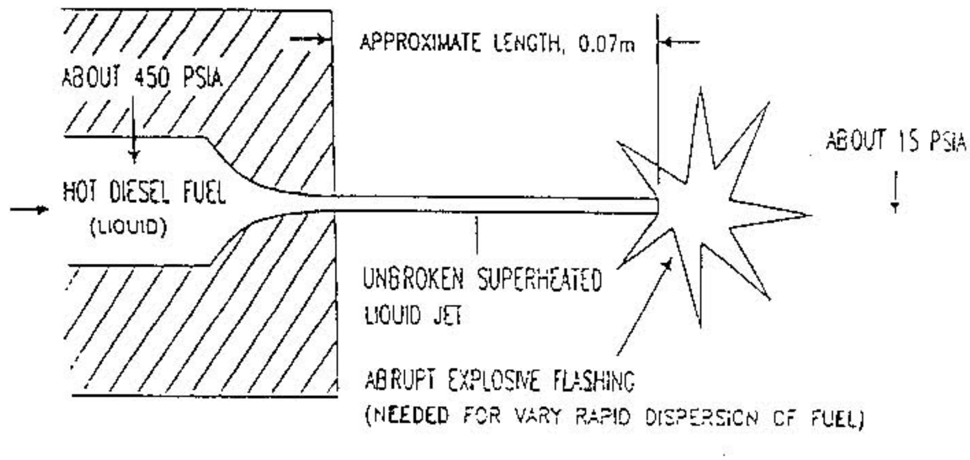


Figure 8c) Example of Two-Phase Rotating Nozzles which Avoid Separation and Abrupt Flashing.



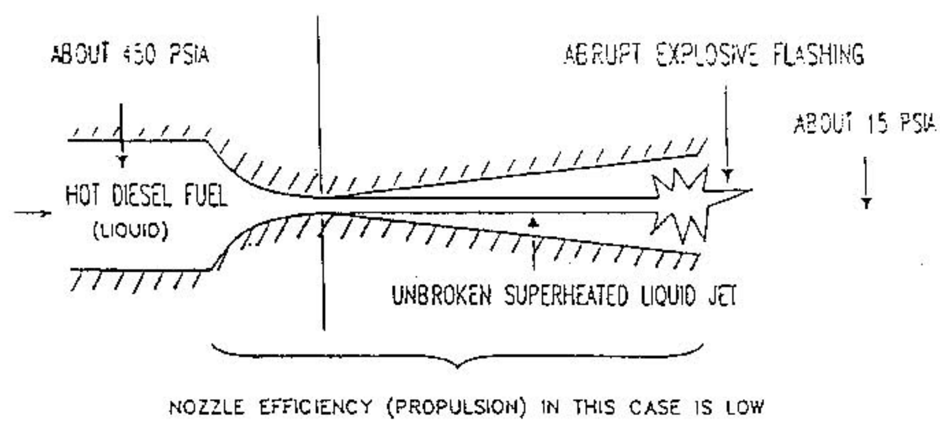


Figure 9. Flashing of Highly Over-Pressurized Diesel Fuel in IC Engine & Flashing of Highly Over-Pressurized Diesel Fuel in DeLaval Nozzles.

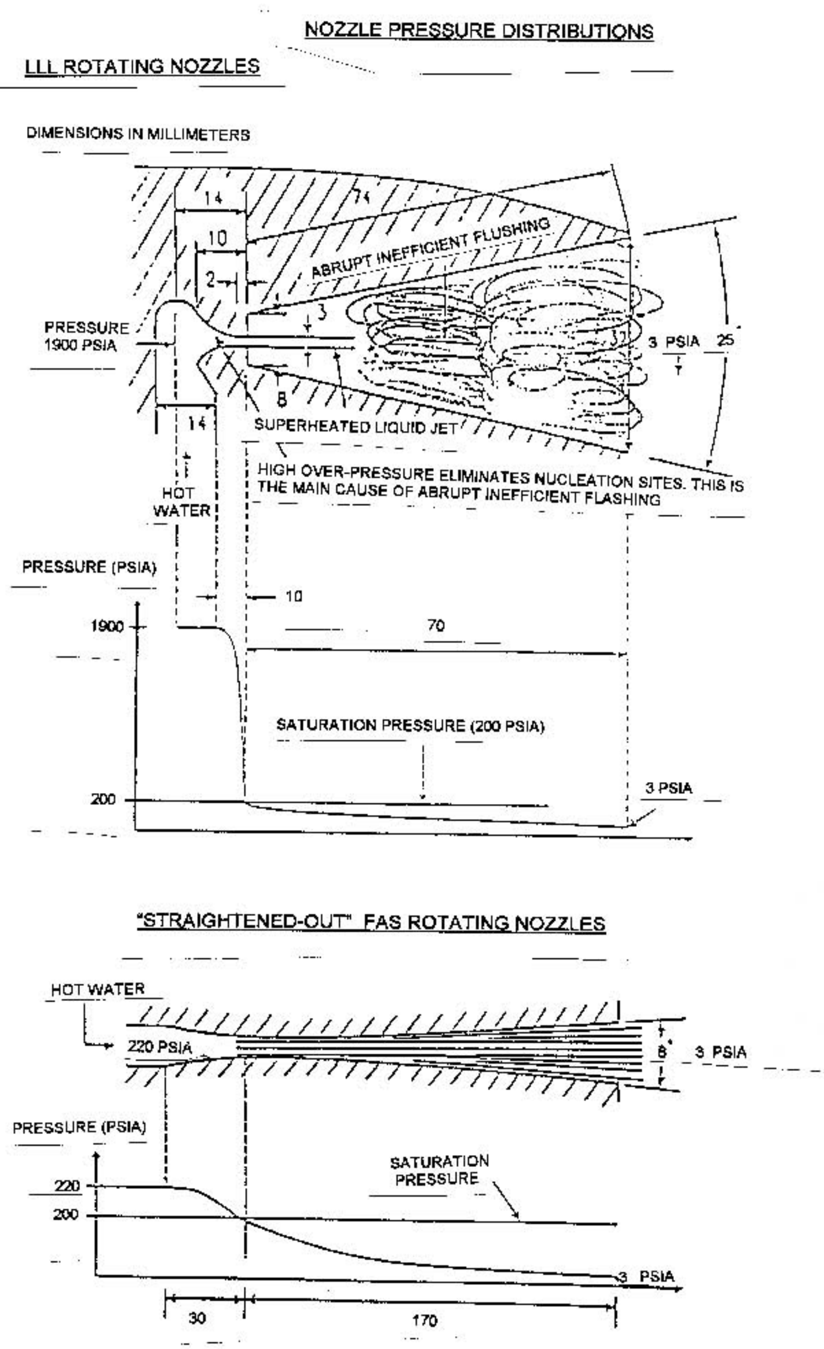


Figure 10. Nozzle Pressure Distributions and Nature of Flashing in the LLL and FAS Nozzles.

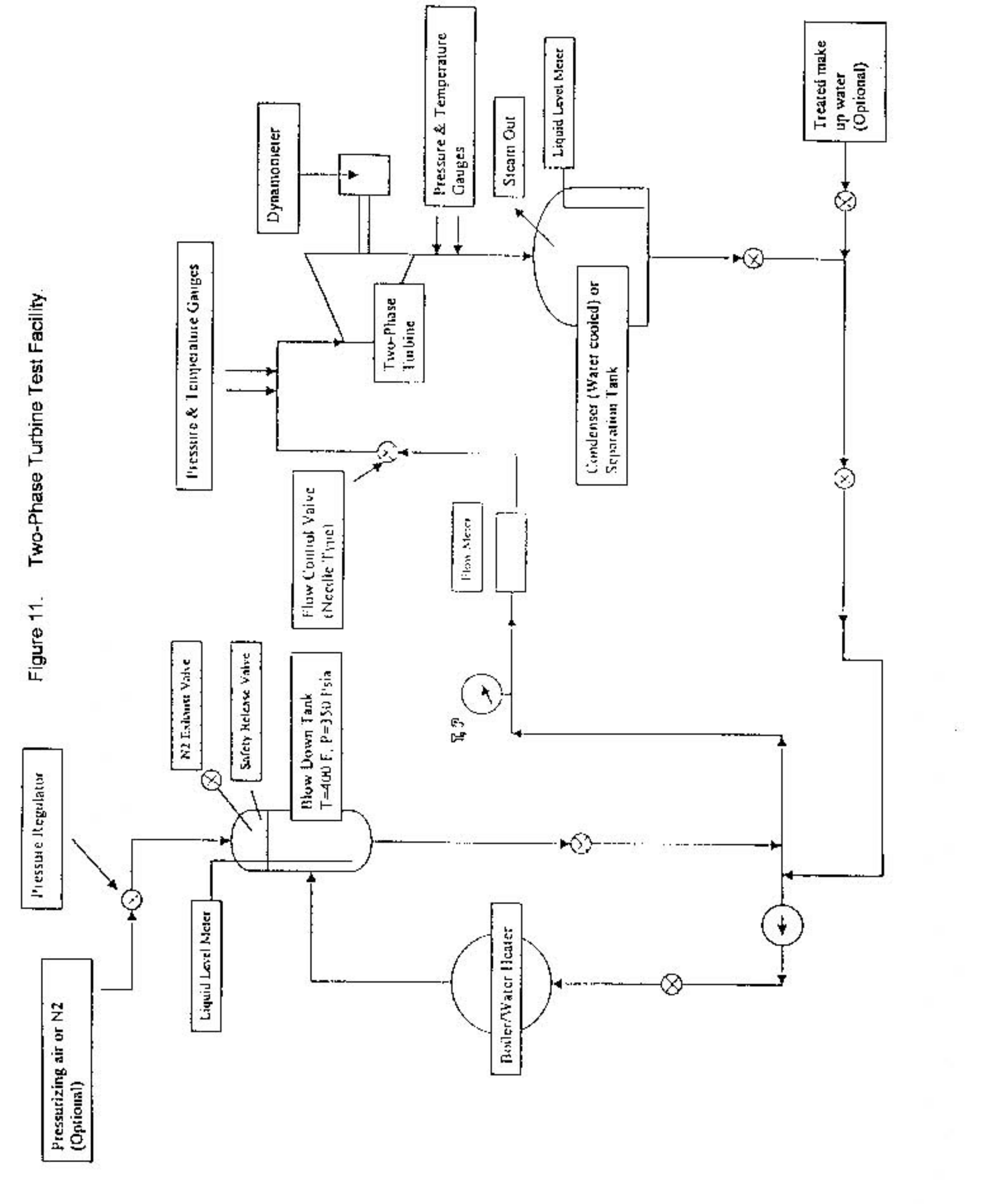


Figure 11. Two-Phase Turbine Test Facility.

Figure 12.

TURBINE-GENERATOR SCHEMATIC DIAGRAM

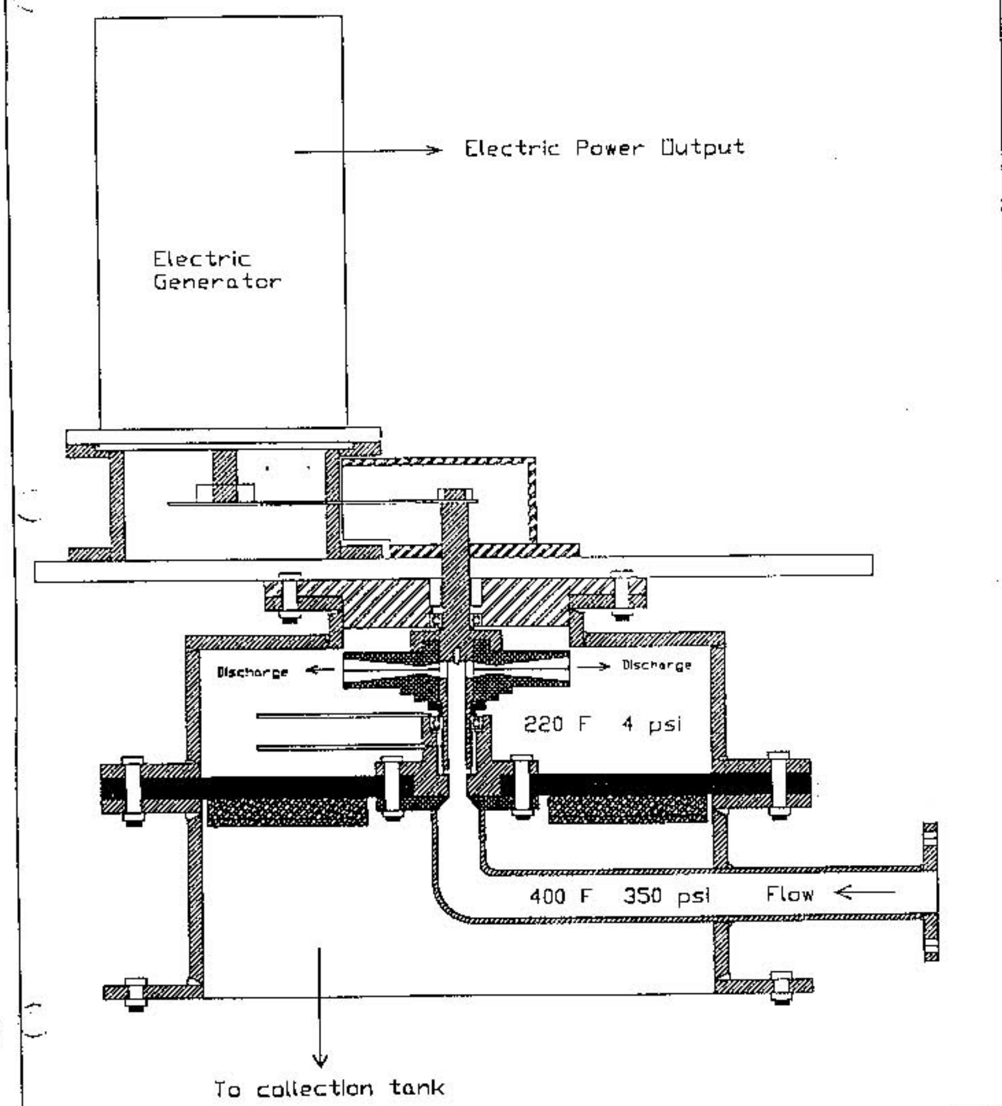


Figure 13. Two-Phase Turbine Rotor with Shaft.

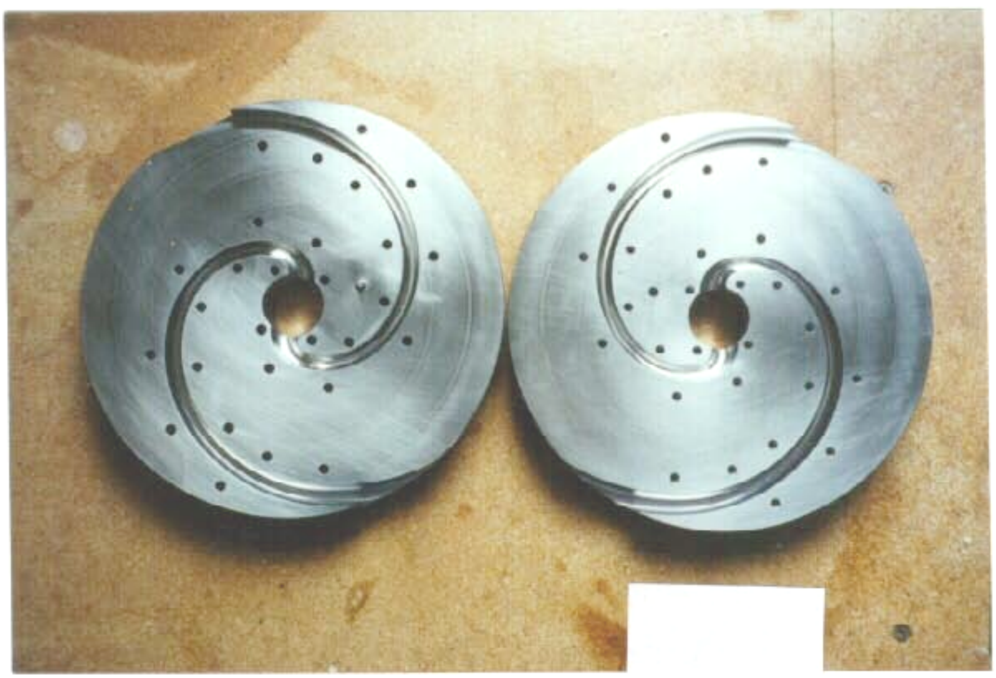


Figure 14. Two Halfs of Turbine Rotor with Curved Reaction Nozzles.

Figure 15. Part of High Temperature Test Facility for Two-Phase Turbine.
(high temperature high pressure water tank is to right,
high temperature high pressure water boiler is painted in blue,
low pressure tank with turbine and generator is behind the boiler,
high temperature boiler water circulation pump is on the floor
between the boiler and high temperature tank,
part of the control panel is also visible between the boiler and the
high temperature tank)

Figure 16. High temperature high pressure water heater (boiler).

Figure 17. Water tubes inside the high temperature water heater.

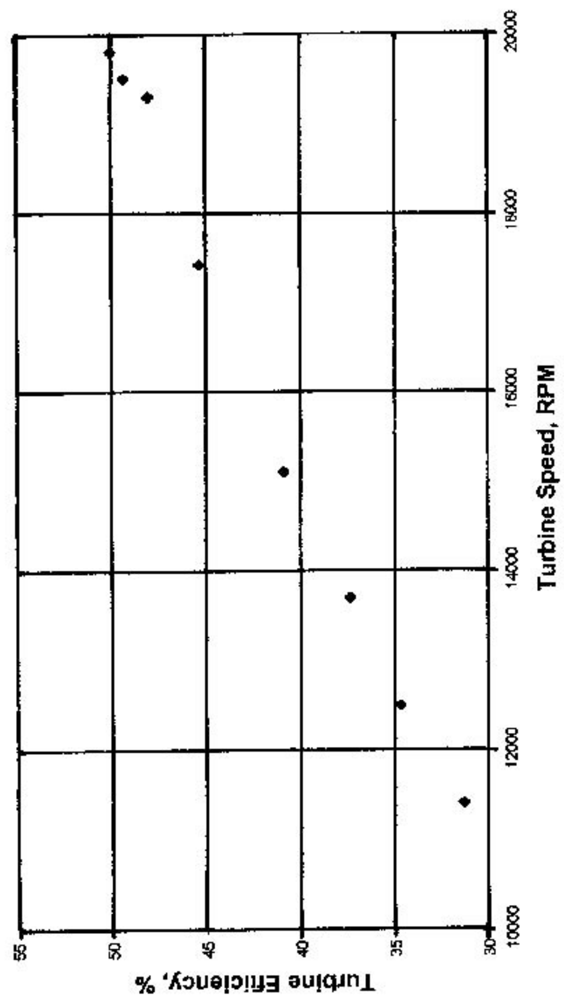


Fig. 18 - Turbine Efficiency